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Collective Motional Resonances and Instabilities of an Electron Cloud Stored in a Penning Trap

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Abstract. We have experimentally investigated the behaviour of an electron cloud confined in a Penning trap at weak superimposed magnetic fields. Exciting the motional frequencies of the electrons by an external drive field we found the axial mode split into two components which were identified as center-of-mass and individual electron oscillations. When the trapping potential was varied, rapid electron loss appeared at numerous values of the applied voltage. They are determined by the relation $n_z\omega_z + n_m\omega_m = \omega_c$. ω_z, ω_m, ω_c are the axial, magnetron, and cyclotron frequency of the trapped electrons, respectively. The reason for this loss is attributed to higher order contributions to the ideal quadrupole trapping potential.

Introduction

The behaviour of an electron cloud confined in Penning traps has been extensively investigated experimentally [1] and theoretically [2] in the general context of the characterization of non-neutral plasmas. In particular the mode structure of the motional oscillations serves to derive properties of the plasma such as density, rotation frequency or shape. The experiments that investigate these properties were performed under conditions, where the temperature of the plasma was low (4K) and the confinement took place far away from the stability limit of the Penning trap. This limit occurs when $\omega_c^{\ 2} = 2\omega_z^{\ 2}, \omega_c = (e/m)B$ being the free electron cyclotron frequency and $\omega_z = (2eV/md^2)^{1/2}$ the axial oscillation frequency, in a trap of characteristic dimension d. B is the magnetic field strength and V, the voltage applied to the trap. In our experiment we confine electrons at weak magnetic fields, approaching the limit of stability. Furthermore the electron temperature is high in the absence of cooling mechanisms.

CP606, *Non-Neutral Plasma Physics IV*, edited by F. Anderegg et al.

Experiment

We used a trap with hyperbolic electrodes of characteristic dimension d = 2 cm. The magnetic field along the z-axis was produced by two Helmholtz coils of 27 cm mean diameter, driven by currents up to 25 A producing a field up to 0.01 T. The trap has been used previously in laser spectroscopic experiments and had holes of several mm diameter drilled into the ring electrode. These holes together with possible misalignments, caused higher order contributions to the trapping potential, which in the ideal case is a quadrupole potential.

The trap was loaded with electrons from a tungsten filament placed several cm below one endcap electrode in pulses of several ms length. After a preset time which could be varied between 10 ms and virtually infinity, detection took place by a tuned circuit consisting of an inductance and the trap electrodes as capacitance. The circuit was weakly excited at its resonance frequency ω_0 (10 MHz). When the positive trap voltage, applied to the ring electrode, is ramped down, the electrons axial oscillation frequency ω_z changes. At a certain voltage ω_z coincides with ω_0. Then the electrons absorb energy from the circuit, which consequently is damped. The r.f. amplitude across the circuit is rectified and the corresponding signal is proportional to the stored electron number. The total number is estimated from observed space charge shifts to about 10^5. The method of detecting the stored electron cloud is in principle nondestructive. During the detection process, however, the electrons gain energy from the tank circuit. In addition they are ejected from the trap as consequence of higher order components in the trapping potential as shown below. This results in a total storage time of only a few second. Therefore we decided to ramp the trapping voltage down to negative voltages. This ensures elimination of all electrons from the trap and each creation-detection cycle starts with a completely empty trap.

Axial oscillation

When we apply an additional r.f. field to one of the electrodes or to the electron gun using it as antenna and sweep the frequency of this field, the electrons become excited whenever it coincides with one of the motional modes. Some of the electrons leave the trap and the motional resonances appear as minima in the detection signal. Fig. 1 shows such a spectrum which contains the fundamental oscillation frequencies ω_m (magnetron), ω_z (axial), and ω_c' (perturbed cyclotron) as well as some linear combinations or multiple of these frequencies. The number of observed combinations depends on the amplitude of the applied r.f. filed. A high resolution scan of ω_z or $2\omega_z$ shows, that these frequencies have two components: A broad asymmetric minimum accompanied on the high frequency side by a narrow more symmetric minimum (Fig.2). Changing the stored ion number shows that the position of the broad minimum is shifted to higher frequency with decreasing electron number while the sharp

minimum does not change its position. When extrapolating both frequencies to vanishing electron number they coincide (Fig. 3). From this we conclude that the broad minimum corresponds to the excitation of the individual electrons in the cloud which experience the space charge of the surrounding cloud, while the sharp minimum is the center-of-mass mode of the whole ion cloud, which, of course, is independent of space charge. This observation is similar to the behavior of a molecular ion cloud stored in a Paul trap [3]. Similarly the appearance of the coherent oscillation of the ion cloud can be explained as a parametric instability of the axial motion under the influence of the additional drive field. As outlined in [3] the excitation of the coherent mode requires a minimum threshold excitation amplitude when the ion motion is damped. As main damping mechanism we consider collisions of the in cloud with rest gas molecules, although our background pressure is of the order of 10^{-9} mbar. This assumption is justified by the fact that the threshold amplitude in our experiments is about 0.2 V whereas in the corresponding experiment on molecular ions it was of the order of 10 V. This change in order of magnitude reflects the difference in collisional cross section of electrons or molecular ions with background molecules.

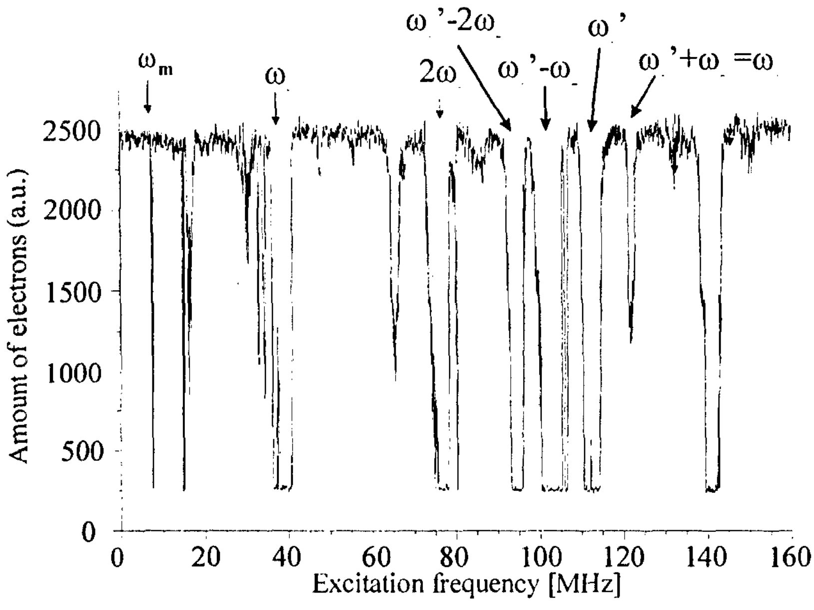

FIGURE 1. Motional spectra of a stored electron cloud in a Penning trap for different amplitudes of a r.f. drive field. Some of the identified resonances are labeled, the others are axial and magnetron sidebands to these frequencies.

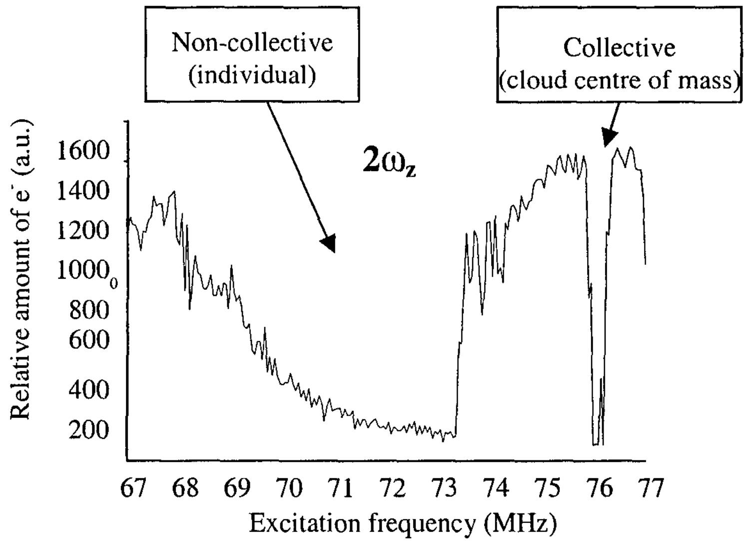

FIGURE 2. High resolution scan of the frequency $2\omega_z$ showing the collective (individual) and non-collective (center-of-mass) components of this mode

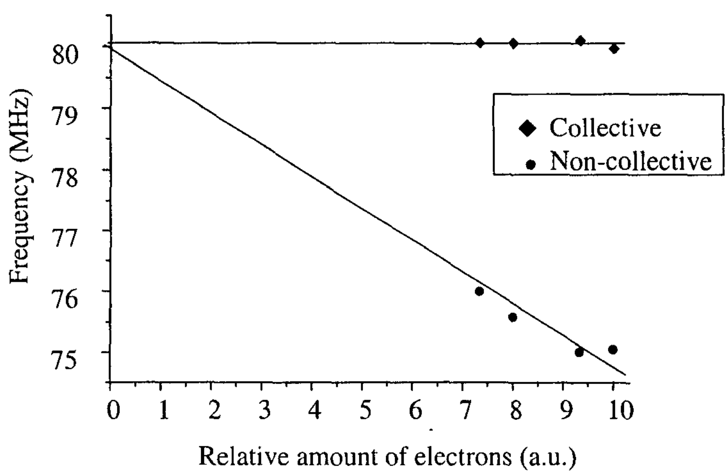

FIGURE 3. Space charge shift of the collective and non-collective resonances. Both frequencies coincide at vanishing electron number

Instabilities In Electron Confinement

When we varied the trapping potential we observed that it was impossible to detect stored electrons at values which are within less than about half of the maximum voltage allowed for stable confinement. This voltage follows from the stability

criterion for Penning traps $\omega_c^{\,2} = 2\omega_z^{\,2}$: $V_{max} = (e/4m)d^2B^2$. Also at distinct lower values of V minima in the detected ion number were observed. The strength of these minima as well as their number increases with the storage time. When the storage time exceeds several seconds, storage of electrons is virtually impossible. Fig. 4 illustrates the observation for a given strength of the magnetic field.

When we plot our observations for different magnetic fields, keeping the storage time constant and calibrating the trapping voltage in percentages of V_{max} we find that the instabilities occur at the same positions. These positions are given by a simple relation between the motional frequencies of the electrons:

$$n_z\omega_z + n_m\omega_m = \omega_c \qquad (1)$$

n_z, n_m are integers.

This relation can be understood in analogy to similar observations in a Paul trap [4,5]: When the trap potential contains multipole components in addition to the ideal quadrupole part it can be described by a series expansion:

$$\Phi(r,\theta,\varphi) = V\sum_{n=0}^{\infty} C_{2n}(r/d)^{2n} P_{2n}(\cos\theta), \qquad (2)$$

where P_{2n} are the Legendre polynomials and C_{2n} are constants. It has been shown for Paul traps [6] that for a potential with nonvanishing coefficients C_{2n} the ion motion becomes unstable for operating conditions which fulfill the relation

$$n_r\omega_r + n_z\omega_z = \Omega \qquad (3)$$

where ω_r and ω_z are the radial and axial oscillation frequencies of the ion motion and Ω the driving frequency of the trapping potential. When we consider an electron orbiting in a constant magnetic field of a Penning trap with the cyclotron frequency ω_c the constant inhomogeneous electric trapping field acts as a time varying electric field in the rest frame of the electron. Thus the cyclotron frequency replaces the driving frequency in eqn. (3). The axial frequency remains unchanged and the radial frequency is replaced by the magnetron frequency yielding eqn. (1). Fig. 4 shows that the observed instabilities can be well assigned to those operating points as predicted by eqn. (1).

Conclusions

We have observed the simultaneous appearance of individual (non-collective) and center-of-mass (collective) resonances in the excitation of the axial oscillation of a stored electron cloud in a Penning trap. At operating point determined by a simple relation between the axial, magnetron and cyclotron oscillation frequencies of the electrons, the confinement becomes unstable. This is attributed to the existence of higher order components in the electric potential of the trap.

Acknowledgements

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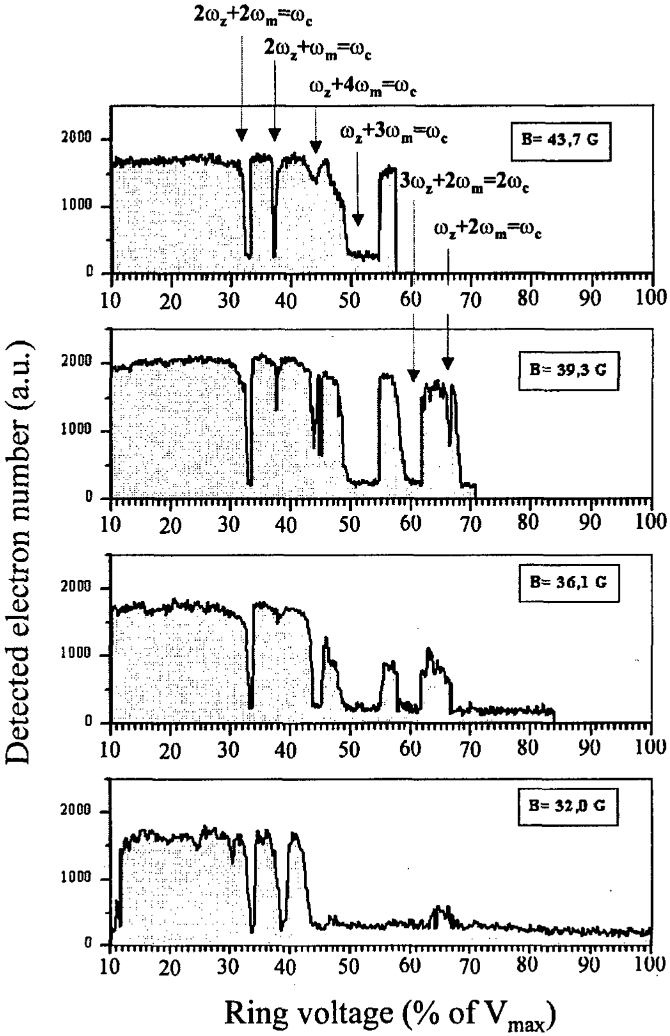

FIGURE 4. Observed instabilities of electron confinement and assignement to predictions following eqn (1)

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